Effect of wave-current interaction on waves and circulation over Georges Bank during storm events

EFFECT OF WAVE-CURRENT INTERACTION ON WAVES AND CIRCULATION OVER GEORGES BANK DURING STORM EVENTS

Dongmei Xie[1] and Qingping Zou[*]

The coupled spectral wave and circulation model SWAN+ADCIRC was applied to investigate the wave-current interaction during storm events over Georges Bank, a large shallow submarine bank on the eastern seaboard of North America that separates Gulf of Maine from the North Atlantic Ocean. The current over the Georges Bank displays a rotary feature over a tidal cycle. The wave-induced current is in the same order as the wind-driven current and generally in the same direction as the depth-averaged tidal current, indicating strong nonlinear wave-current interaction. The magnitude of wave-induced current reaches 0.07 m/s at low tide and 0.2 m/s at the other three tidal phases. The effect of wave-current interaction on waves at the four tidal phases is also analyzed. The role of Georges Bank in dissipating wave energy is most significant at rising mid-tide and high tide, which is close to the storm peak. At rising mid-tide, the wave height is decreased by 0.3 m to 0.5 m over the majority of the bank when the wave propagates in the same direction as the current. At falling-mid tide, the wave height is increased by 0.5 m at the southern flank and decreased by 0.5 m at the northern flank of the bank.

Keywords: SWAN; ADCIRC; wave-induced current; Georges Bank

INTRODUCTION

Georges Bank is a large shallow submarine bank on the eastern seaboard of North America that separates Gulf of Maine from the North Atlantic Ocean, with its minimum water depth around 10 m. The area has one of the most productive ecosystems in the world, mainly due to the unique physical processes of the clockwise circulation and turbulence mixing over the bank (e.g. Franks and Chen 2001).

The investigation of circulation over Georges Bank has been carried out both by measurements (e.g. Limeburner and Beardsley 1996; Pettigrew et al. 2005) and numerical modeling (e.g. Naimie 1996; Xue et al. 2000). Over the bank, the circulation exhibits a rotary feature and the dominant M2 tidal currents range between 0.3m/s on the southern flank to 1.0m/s at the edge of the northern flank (Greenberg 1983). These studies focused on elucidating the general circulation pattern. Recently, Sun et al. (2013) investigated the impact of wave-current interaction on storm surge modeling in the Gulf of Maine. However, the role of waves in contributing to the current field over the bank has yet to be studied.

Waves over Georges Bank also need to be addressed. The shallow bathymetry and rotating current over the bank have a significant effect on wave propagation and transformation from the North Atlantic Ocean into the Gulf of Maine. The wave energy is dissipated over the bank, which can generate wave-induced current due to wave radiation stress gradients (Longuet-Higgins and Stewart 1964; Zou et al. 2006).

In this study, the wave-current interaction over Georges Bank was investigated, as well as its effect on waves and circulation using the coupled SWAN+ADCIRC model (Dietrich et al. 2011). Numerical simulations were carried out on the hydrodynamic response in the Gulf of Maine to the 2007 Patriot's Day storm. The effect of currents on wave propagation is analyzed. The contribution of waves to circulation over Georges Bank through wave radiation stress (Longuet-Higgins and Stewart 1964) is also examined. To our knowledge, no comprehensive studies of wave-current interaction over Georges Bank and its impact on waves and circulation have been carried out.

MODEL SETUP

The wave-current interaction process over the Georges Bank was examined during the Patriot's Day storm in 2007 using the fully coupled SWAN+ADCIRC model (Dietrich et al. 2011). The third generation spectral wave mode Simulating WAves Nearshore (SWAN) solves the wave action density equation without pre-defined spectral shape by accounting for multiple processes, including wind-wave generation, nonlinear wave triad and quartet interactions, wave dissipation by whitecapping, bottom friction and depth-induced wave breaking and wave refraction by water depth and current (Booij et al. 1999; Ris et al. 1999). Zijlema (2010) applied a Gauss-Seidel technique to extend SWAN to run on

[1] Department of Civil and Environmental Engineering, University of Maine, Orono, ME 04469, USA
*Corresponding author: qingping.zou@maine.edu

unstructured meshes. The two-dimensional depth-integrated ADvanced CIRCulation (ADCIRC) model solves the shallow tide equations using finite element method for hydrodynamic circulation along shelve, coasts and within estuaries (Luettich et al. 1992; Westerink et al. 1994). The SWAN and ADCIRC are coupled by sharing the same unstructured mesh and exchanging integrated parameters (Dietrich et al. 2011). While ADCIRC passes water level and depth-averaged current to SWAN, SWAN integrates over spectral domain and passes wave radiation stress to ADCIRC. The coupled model has been successfully applied for storm surge and circulation simulations (e.g. Dietrich et al. 2011; Sebastian et al. 2014; Xie et al. 2016; Zou and Xie 2016).

Figure 1 shows the model coverage for wave and circulation simulation in the Gulf of Maine. The model domain covers the Gulf of Maine and adjacent waters. The open boundary is located well off the continental shelf break to simplify the specification of boundary conditions while reasonably resolving the circulation and wave features in the Gulf of Maine. Computational efficiency is also taken into account for the selection of model domain. The grid resolution ranges from 25,000 m along the offshore boundary to 15 m in the coastal area. The grid is also refined over Georges Bank to resolve the rapidly changing bathymetry in that area.

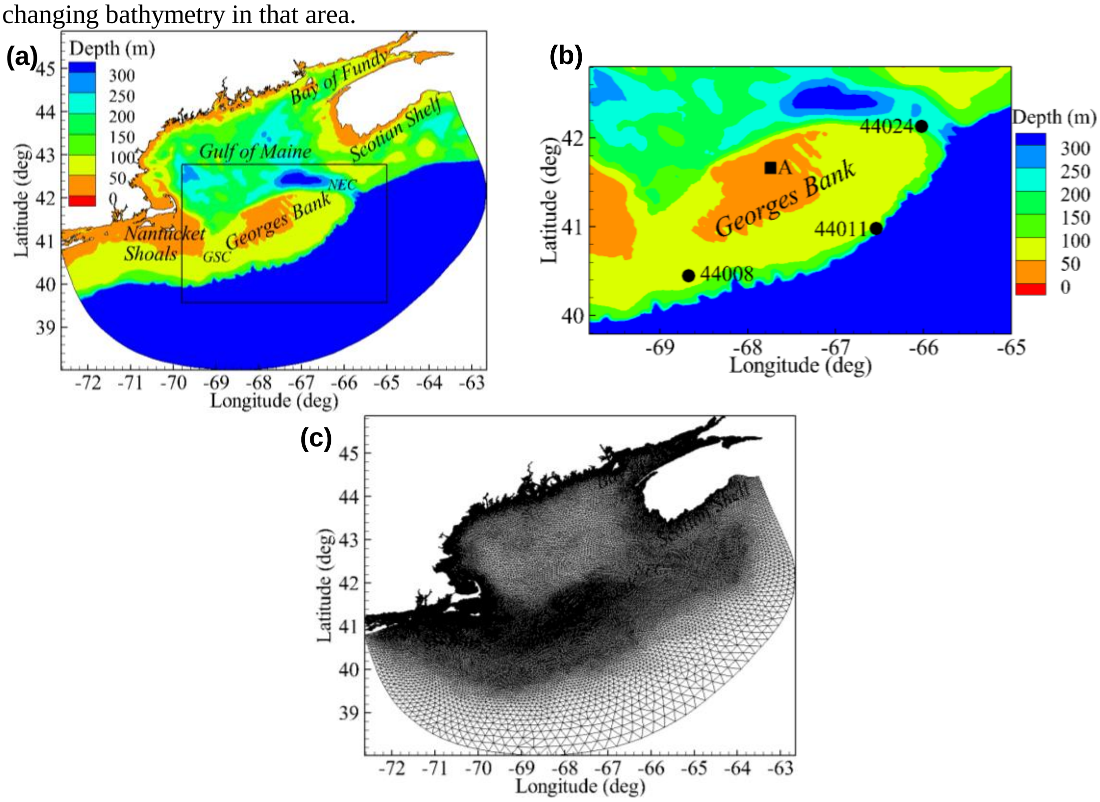


Figure 1. Model domain and bathymetry for the Gulf of Maine and adjacent waters. (a) Model domain and bathymetry for the Gulf of Maine. Topographic features in the text are GSC: Great South Channel, NEC: Northeast Channel. (b) The Georges Bank and adjacent waters indicated by the square box in (a). The circles represent wave buoy locations and the black-filled square marked by A is one location on the 20m contour line over Georges Bank. (c) The unstructured mesh for the Gulf of Maine.

The selected storm event, the 2007 Patriot's Day Storm, has an intensity similar to a moderate category II hurricane and generated large storm surge and waves in the Gulf of Maine, causing severe coastal flooding and damage to coastal infrastructures (Marrone 2008; Zou and Xie 2016). The 6-hourly NCEP North American Regional Analysis (NARR) wind and pressure is used as surface pressure and wind forcing for circulation and wave simulation for the storm event. Zou and Xie (2016) validated the NARR wind and pressure data in the Gulf of Maine, indicating good agreement between the reanalysis dataset and buoy measurements.

Detailed information on the model parameters can be found in Zou and Xie (2016). For surge and circulation simulation in the Gulf of Maine, the eight most significant astronomical tide constituents (M2, S2, N2, K2, K1, P1, O1 and Q1) were used to drive the model along the open boundary. A constant lateral viscosity of 5 m^2/s was specified (Yang and Myers 2007; Bunya et al. 2010). Garratt's drag formula (Garratt 1977) was used with a cap of $C_d \leq 0.0035$ as the surface air-sea drag coefficient.

The hybrid friction relationship was used to specify a spatially varying bottom friction coefficient depending on water-depth (Luettich and Westerink 2006).

For wave simulation, the 2D wave spectra output by SWAN hindcast in the Western North Atlantic Ocean was used as the offshore boundary conditions. The wave action density was obtained by solving the wave action density balance equation with a prescribed spectrum frequency band ranging from 0.031384 to 1.420416 Hz on a logrithmic scale. When SWAN and ADCIRC were coupled, the two models exchange information every 600 s.

Three cases were run: (1) ADCIRC only for tide-surge and associated current simulation without wave effect; (2) SWAN only for wave simualtion without temporal varying water level and currents; (3) the tightly coupled SWAN+ADCIRC to include tide-surge and wave interaction.

MODEL RESULTS

The predicted wave parameters and current by the model was first compared with buoy observation over or near the Georges Bank. The significant wave height and peak wave period were compared with buoy measurements at buoy 44008 and 44011 over the Georges Bank shown in figure 1. At both buoy locations, the model reasonably reproduced the observed wave growing and decaying processes. The effect of water level and current on waves is negligible at the peak of the storm. However, both the significant wave height and peak wave period are slightly modified after the peak of the storm by the current effect.

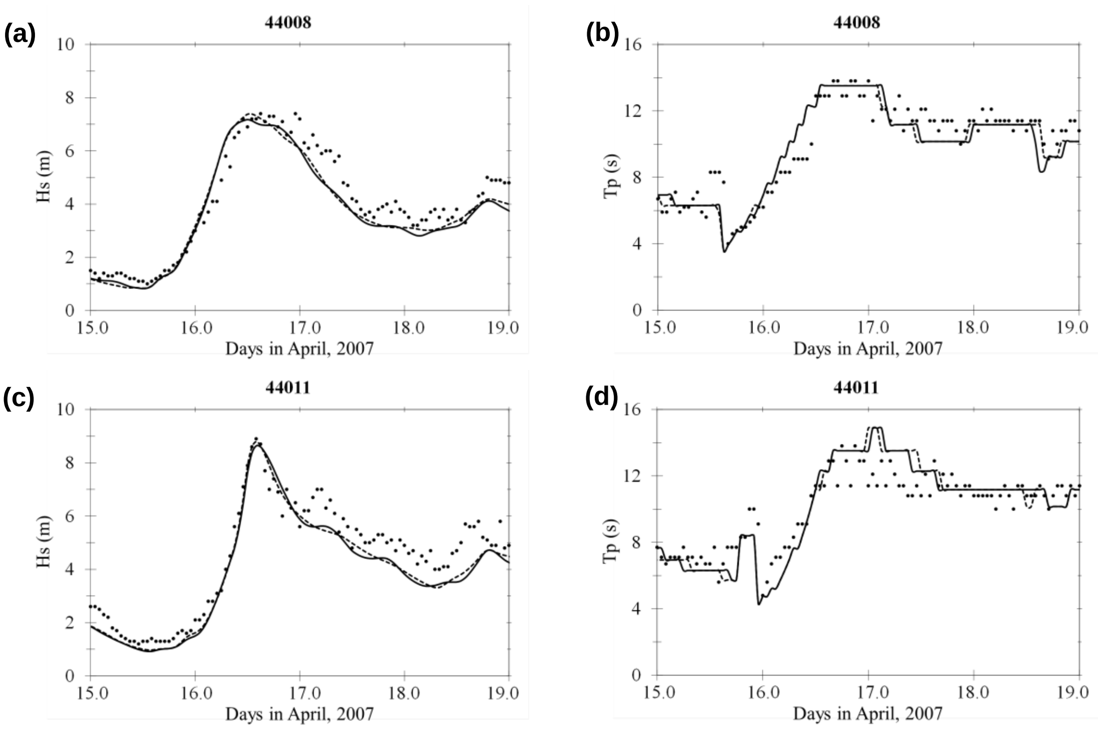


Figure 2. Comparison of significant wave height and peak wave period. Dots: observations; solid and dash line: model results with and without current effect.

Figure 3 shows the comparison of predicted current speed and direction with the measurements by buoy 44024, which is located in the Northeastern Channel to the east of Georges Bank. Both the phase and direction of depth-averaged current were reasonably predicted with and without considering wave effect. The current speed is slightly underestimated by the model, however, the result is improved with wave effect.

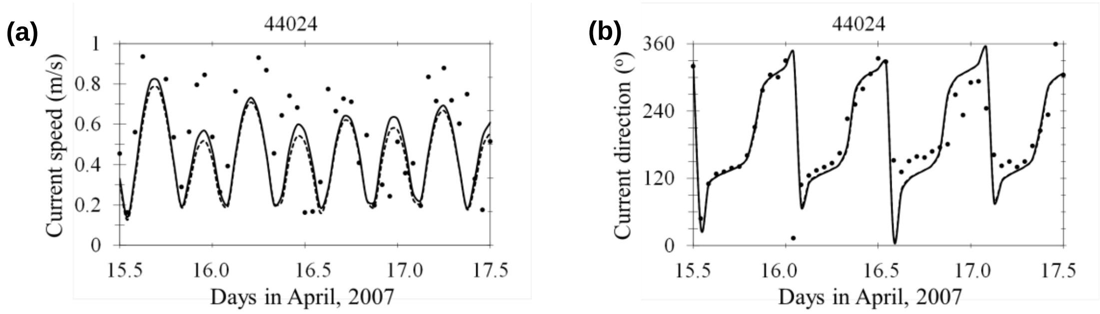
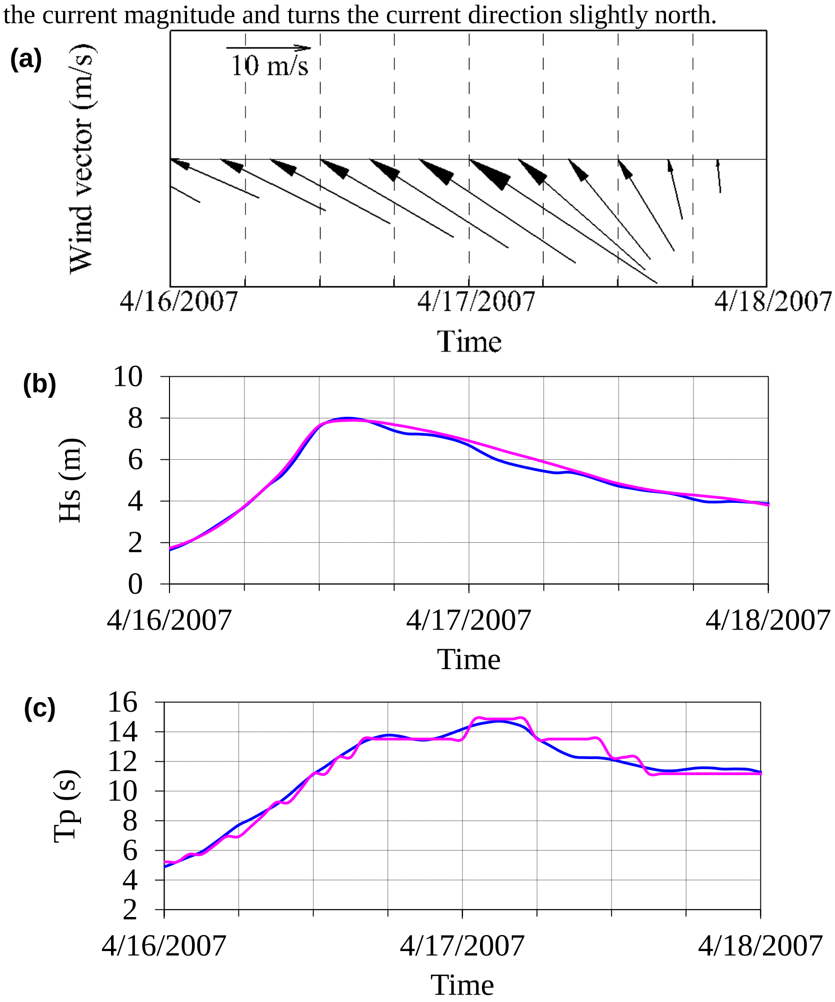


Figure 3. Model-data comparison of current speed and direction. Dots: observations; solid and dashed line: model results with and without wave effect.

The effect of wave-current interaction on waves and circulation was then carried out. The time series of waves, wave level and current at point A in figure 1 was first plotted in figure 4. Point A is selected mainly due to its shallow tide depth over the bank. During April 16th to 18th, the storm generated persisting southeastern wind in the Gulf of Maine, resulting in large waves and wind-driven current over the Georges Bank. The significant wave height reaches 8.0 m at storm peak and the surge level is 0.4 m. At point A, the role of wave-current interaction on waves and water level is not significant. However, the current is significantly larger with wave effect. The wave-induced current is 0.2 m/s at the storm peak, with same magnitude of wind-driven current. The current direction is slightly veered to the north by taking into wave-current interaction. When wave propagates from the open Northwestern Atlantic Ocean into the Gulf of Maine over the Georges Bank, wave energy is significantly dissipated by bottom friction due to the shallow bathymetry over the bank, generating wave radiation stress gradient in the cross-bank direction. The wave radiation stress gradient hence increases the current magnitude and turns the current direction slightly north.



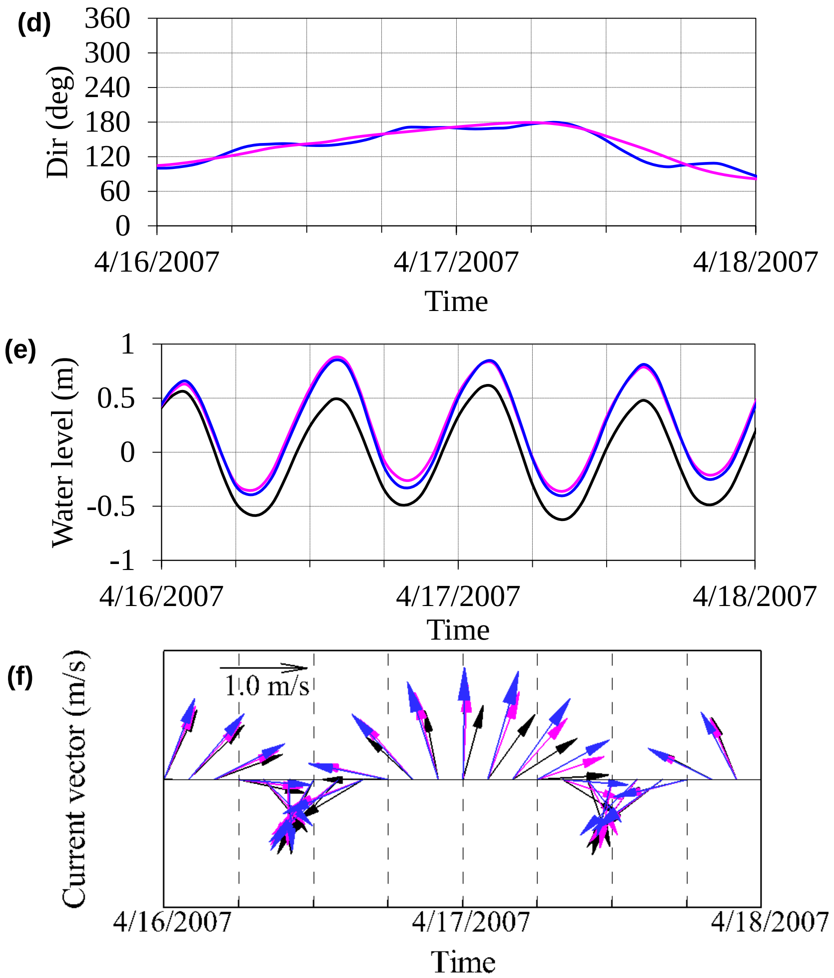


Figure 4. Time series of wind, wave, water level and current at point A over Georges Bank in figure 1. (a) Wind speed; (b) Significant wave height; (c) Peak wave period; (d) Mean wave direction; (e) Water level; (f) Current velocity. The blue and purple solid line represent the results with and without wave-current interaction; the black solid line in (e) and (f) represents the tidal level and tidal current

Due to the rotary feature of current over Georges Bank, the effect of wave-current interaction on current and wave field is analyzed at four different tidal phases during the Patriot's Day Storm. The four tidal phases analyzed are low tide at 0900UTC, rising mid-tide at 1200UTC, high tide at 1500UTC and falling mid-tide at 1800UTC on April 16th. Figure 5 shows the depth-averaged current with the wave-current interaction and the wave-induced current at the four tidal phases. The current speed at the northern flank of the bank is larger compared to that of the southern flank in general and reaches its maximum value of 1.5 m/s where water depth is the shallowest. At low tide, the current flows to northwest. At rising mid-tide, the flow direction is pointing north. At high tide, the current is in the northeast direction. At falling mid-tide, the current is flowing to the south. The current magnitude is larger at rising and falling mid-tide compared to low and high tide. As the wave propagates from the open ocean over Georges Bank into the Gulf of Maine, the wave energy is dissipated by bottom friction, causing sharp decrease of significant wave height. Since the wave radiation stress is proportional to the square of wave height, the corresponding radiation stress gradient will impose extra momentum flux on the circulation and result in significant wave-induced current, which will increase the mass transport and potentially impact the ecosystem over the bank. At low tide, the wave-induced current is small and reaches its maximum value of 0.07 m/s in the center of the bank. The wave-induced current is significantly larger at the other three tidal phases, when the larger wave radiation stress gradient is present. The maximum wave-induced current is approximately 0.2 m/s, in the same order with the residual tidal current over the bank. Also, the direction of wave-induced current is closely aligned with the tidal current, indicating strong nonlinear wave-current interaction.

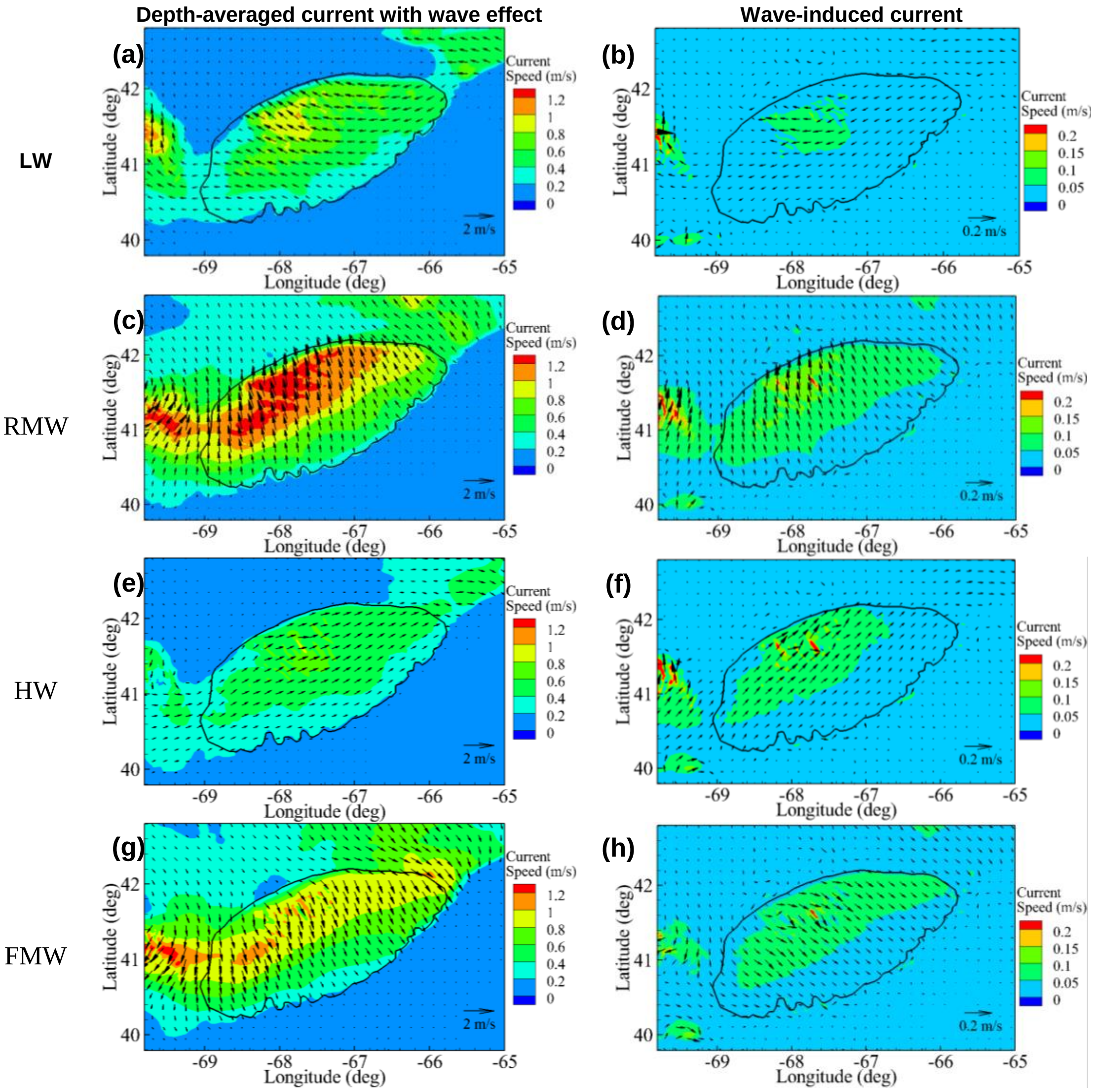
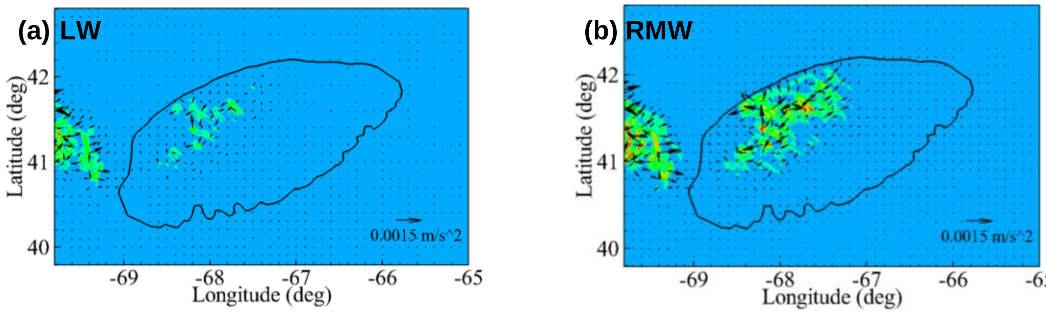


Figure 5. Depth-averaged velocity during the storm. (a)(c)(e)(g) show the depth-averaged current with wave-current interaction at four tidal phases; (b)(d)(f)(h) show the wave-induced current at four tidal phases. The four tidal phases are denoted as LW (low tide), RMW (rising mid-tide), HW (high tide) and FMW (falling mid-tide) respectively.



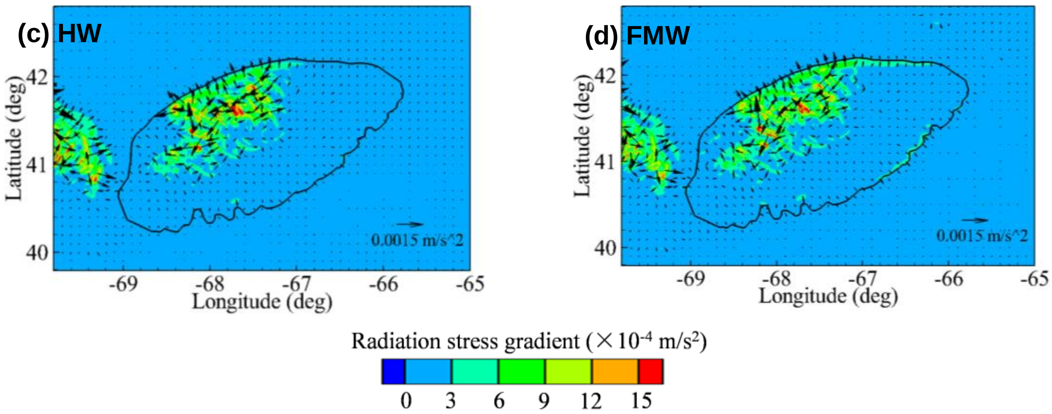
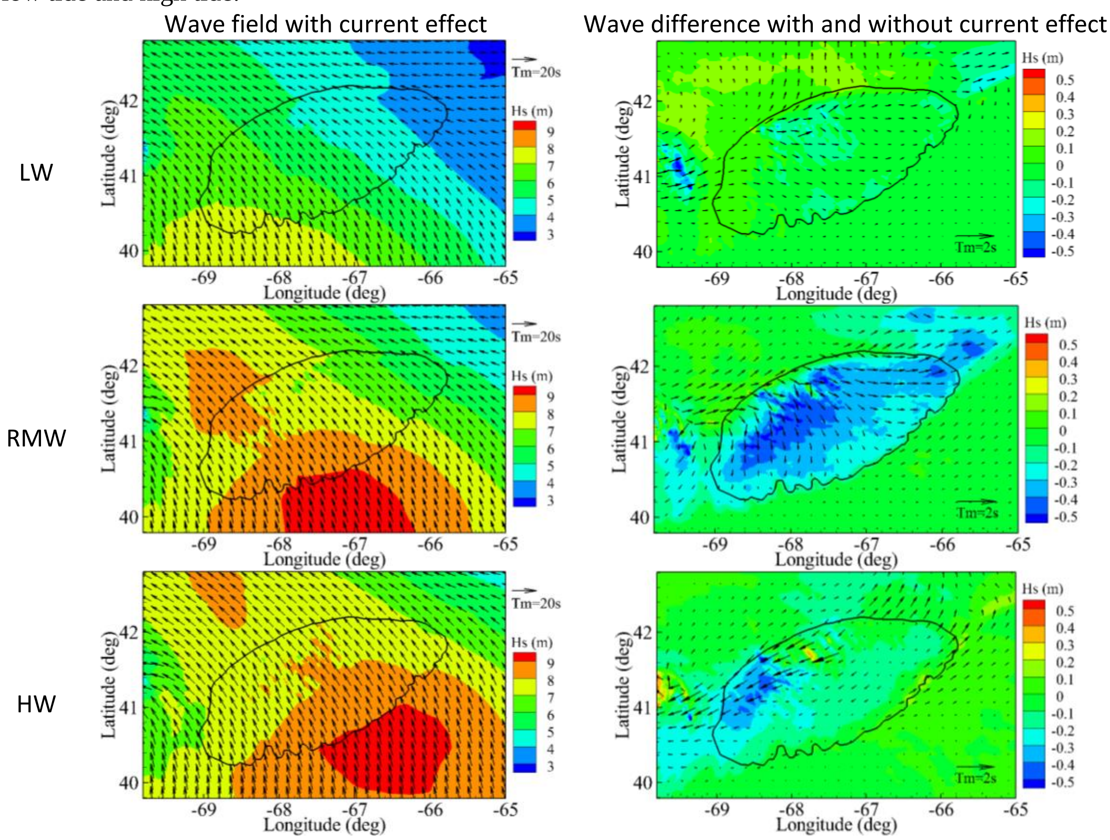


Figure 6. Wave radiation stress gradients at four tidal phases: (a) Low tide; (b) Rising mid-tide; (c) High tide; (d) Falling mid-tide

The effect of wave-current interaction on waves at the four tidal phases is also analyzed. Figure 7 shows the wave fields at the four tidal phases. The storm generated significant wave height exceeding 5.0 m over the bank during the storm event. The role of Georges Bank in dissipating wave energy is most significant at rising mid-tide and high tide, which is close to the storm peak. At these two tidal phases, the wave energy is significantly dissipated in the cross bank direction. The George Bank also plays a role in blocking waves from propagating from open ocean into the Gulf of Maine due to the rapidly changing bathymetry at the shelf break. At the rising mid-tide, the wave propagates in the same direction as the current direction on Georges Bank, the wave height is decreased by 0.3 m to 0.5 m over the majority of the bank. At the falling-mid tide, the wave propagates in the opposite direction as the current, resulting in increased wave height at the southern flank and decreased wave height at the northern flank of the bank. The effect of wave-current interaction on waves is comparatively small at low tide and high tide.



FMW

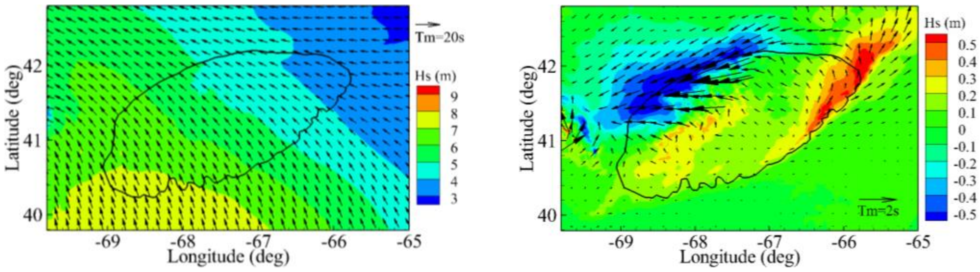


Figure 7. Wave field during the storm. (a)(c)(e)(g) show the wave field with the wave-current interaction at four tidal phases; (b)(d)(f)(h) show the difference in waves with and without wave-current interaction. The color in all plots represents the significant wave height. The arrows represent the mean wave direction and the length of the arrow represents the mean wave period.

CONCLUSION AND DISCUSSION

The coupled spectral wave and circulation model SWAN+ADCIRC was applied to investigate the wave-current interaction over Georges Bank during the Patriot's Day Storm. The current over the Georges Bank presents a rotary feature over a tidal cycle. At low tide, the current flows to northwest. At rising mid-tide, the flow direction is pointing north. At high tide, the current is in the northeast direction. At falling mid-tide, the current is flowing to the south. Current magnitude is larger at rising and falling mid-tide compared to low and high tide. Analysis was carried out at the four tidal phases respectively. The wave-induced current is in the same order as the wind-driven current. At low tide the wave-induced current is small with its maximum value of 0.07 m/s in the center of the bank. The wave-induced current is significantly larger at the other three tidal phases, when the larger wave radiation stress gradient is present. The maximum wave-induced current is approximately 0.2 m/s. Also, the direction of wave-induced current is closely aligned with the tidal current, indicating strong nonliear wave-current interaction.

The effect of wave-current interaction on waves at the four tidal phases is also analyzed. The role of Georges Bank in dissipating wave energy is most significant at rising mid-tide and high tide, which is close to the storm peak. At rising mid-tide, the wave height is decreased by 0.3 m to 0.5 m over the majority of the bank when the wave propagates in the same direction as current. At falling-mid tide, the wave height is increased by 0.5 m at the southern flank and decreased by 0.5 m at the northern flank of the bank. The effect of wave-current interaction on waves is negligible at the other two tidal phases when the wave is relatively small.

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